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ABSTRACT

In oil refineries and chemical plants, there exist large amount of hot fluids. The typical hot fluids include the hot medium water for the process, the condensed hot water, the hydrofining diesel and the hydrofining gasoline etc. These hot fluids from the different processes have the temperature above 95°C typically, and they need to be cooled down to the temperature required by their processes. The air cooling and/or water cooling are used to cool these fluids, and the large amount of thermal energy is wasted in addition to the power and water consumptions for the cooling. The thermal energy in the hot fluids can be recovered by ORC (Organic Rankine Cycle) to generate power. At the same time, the hot fluids can be cooled down to the required temperatures, and thus the power and the water, which are consumed to cool the hot fluids, can be saved. The author applied single stage and cascaded ORC to recover the thermal energy in the hot fluids in refineries and chemical plants, and at the same time to cool the hot fluids to the required temperatures. For the hot fluids with large flow capacities and high required temperature drops, cascaded ORC systems are used to increase the thermal efficiency. In this paper, the author presented two ORC application cases in refineries: a single stage ORC power plant with a screw expander is used to cool down the hydrofining gasoline from the process, which is the first reported case in the world that the hot hydrofining gasoline enters the ORC directly, and a novel cascaded ORC power plant with screw expanders is used to cool down the hot medium water from the refining process. For the hot medium water application, the author compared the thermal efficiencies for both the single stage and the novel cascaded ORC systems. For the same flow capacity and the same temperature drop of the hot medium water, the thermal efficiency of the cascade ORC is 13.2% higher than the single stage ORC.

1. INTRODUCTION

In oil refineries and chemical plants, there exist large amount of hot fluids, such as, the hot medium water for the refining processes, the condensed hot water, the hydrofining diesel and the hydrofining gasoline etc. These hot fluids from the different processes have the temperature above 95°C typically, and they need to be cooled down to the temperature required by their processes. Typically, the hot medium water or the condensed hot water from the refining processes need to be cooled down to 70°C, where air cooled heat exchangers are used. The hydrofining diesel and gasoline from the refining process need to be cooled down to 50°C, which the air-cooled heat exchangers are used first to cool the fluids down to 70°C in order to prevent the scaling of the water cooled heat exchangers, and then the fluids are cooled further by cycling cooling water down to 50°C. Obviously, these cooling processes have the following results:

- A large amount of thermal energy is wasted. The author did an analysis on a typical medium size oil refinery. If the current wasted thermal energy can be recovered by ORC (Organic Rankine Cycle) or by the cascaded steam and organic Rankine cycles (Tang Y., 2014) to generate the electricity. The total electrical power consumption of the refinery can be reduced roughly by one third. Some refining processes can output the power instead of consuming the power.

- The cooling processes consume a large amount of power. The power is consumed by the cooling fans of the radiators, the cooling water pumps and the cooling water towers. A medium size refinery consumes 5 – 10MW cooling power, most of which can be saved, if the thermal energy is recovered by the power generation.

- The cooling water towers consume a lot of fresh water, most of which can also be saved, if the thermal energy is recovered by the power generation.

The author has applied ORC to refineries and chemical plants for the last few years. In this paper, the author reported two ORC application cases in refineries:

- Case 1: a single stage ORC power plant with a screw expander is used to cool down the hydrofining gasoline from the process, which is the first reported case in the world that the hot hydrofining gasoline enters the ORC directly. The hot hydrofining gasoline with 135°C enters the ORC power plant to be cooled down to the required 70°C, and at the same time over 500 kW net power is output from the power plant and the power consumption of the hot gasoline radiator is saved.

- Case 2: a novel cascaded ORC power plant with screw expanders is used to cool down the hot medium water from the refining process. The hot medium water with 118°C enters the ORC power plant to be cooled down to the required 70°C, which then is sent back to the refining process for cycling. Over 900 kW net power is output from the power plant, and at the same time the power consumption of the hot water radiator is saved.

2. AN ORC POWER PLANT WITH A SCREW EXPANDER USED FOR HOT HYDROFINING GASOLINE

Fig. 1 shows the hot gasoline ORC power plant installed at Sinopec Yanshan Refinery, Beijing, China. The hydrofining gasoline from the refining process goes through the evaporator and then preheater of the ORC power plant directly, and its temperature drops from 135°C to 70°C. The power plant was put into operation in October, 2015, and it is the 1st ORC power plant in the world powered by the hot gasoline. The power plant is explosion proof and it was designed with all the necessary redundancy requested by the refinery standard and regulations.

Fig. 1: the hot gasoline ORC power plant installed at Sinopec Yanshan Refinery, Beijing, China

Table 1 shows the designed specifications of the power plant. The acceptation test results indicated that the power plant achieved 546 kW of net power output at the design condition. As the isentropic efficiency of screw expander model SKYe297 is as high as 88%, and also due to the improved evaporative condenser design and the improved evaporator design, the thermal efficiency based on the net power output of the power plant reaches 9.7%. Before the power plant was installed, the hydrofining gasoline was cooled down from 135°C to 70°C by the air-cooled heat exchangers, and then cooled down further from 70°C to 50°C by the water-cooled heat exchangers. After the power plant was on the grid, the fans of air-cooling heat exchangers were shut down. As a result, in addition to the power generated by the power plant, the shutdown of the cooling fans gained further power saving.

Table 1: power generation units installed at Sinopec Yanshan Refinery, Beijing, China

Orc power plant model	KE900-96S-1-50
Working fluid	R245fa
Screw expander model	SKYe297
Designed evaporation temperature (°C)	96
Designed condensing temperature (°C)	25
Condenser type	Evaporative
Fuel type	Hydrofining gasoline
Fuel inlet temperature (°C)	135
Fuel outlet temperature (°C)	70
Fuel flow capacity (t/h)	125
Generator nominal power (kW)	900
Generator type	Induction
Generator voltage (V)	6300
Gross power at design conditions (kW)	650
Net power at design conditions (kW)	540

3. NOVEL CASCADED ORGANIC RANKINE CYCLES WITH SCREW EXPANDERS

In the above hot gasoline ORC power plant, a simple single stage organic Rankine cycle is used. Fig. 2 shows such a typical organic Rankine cycle. For the hot fluids with high flow capacity and high required temperature drop, the author applied the cascaded organic Rankine cycles, shown as in Fig. 3, in the practice. When the hot fluid comes out of the evaporator of the high temperature loop at position 1 of Fig. 3, most of the hot fluid then enters the evaporator of the low temperature loop. Only small portion of the hot fluid enters the preheater of the high temperature loop. When the hot fluid comes out of the preheater of the high temperature loop at position 2, its temperature can be as low as a few degree C higher than the temperature of the refrigerant entering the preheater depending on the preheater type and design. The fluid temperature at position 2 typically far lower than the required overall returning temperature at position 4. The temperature of the hot fluid, which comes out of the preheater of the low temperature loop, is higher than the returning temperature at position 4. The mixture of the hot fluid from both the preheaters of high and low temperature loops then achieves the overall returning temperature.

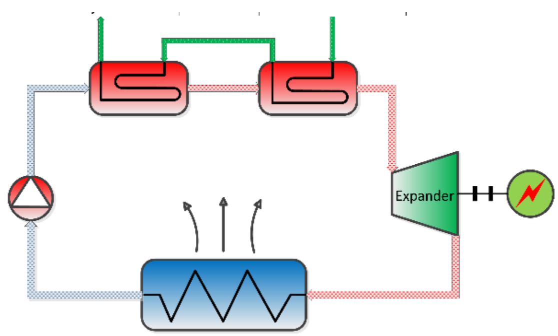

Fig. 2: a typical single stage organic Rankine cycle

In refineries and chemical plants, some hot fluids, which come out of the ORC power plant, need further cooling. For example, in the above hot gasoline ORC power plant, the hydrofining gasoline from the ORC power plant needs to be cooled down further to 50°C. In the applications similar to this, if the cascaded ORC is used, the hot fluid from the preheater of the high temperature loop can achieve the targeted temperature, so that it will not require further cooling and thus save the cooling power. Only portion of the hot fluid from the preheater of the low temperature loop needs to be cooled down further to the targeted temperature.

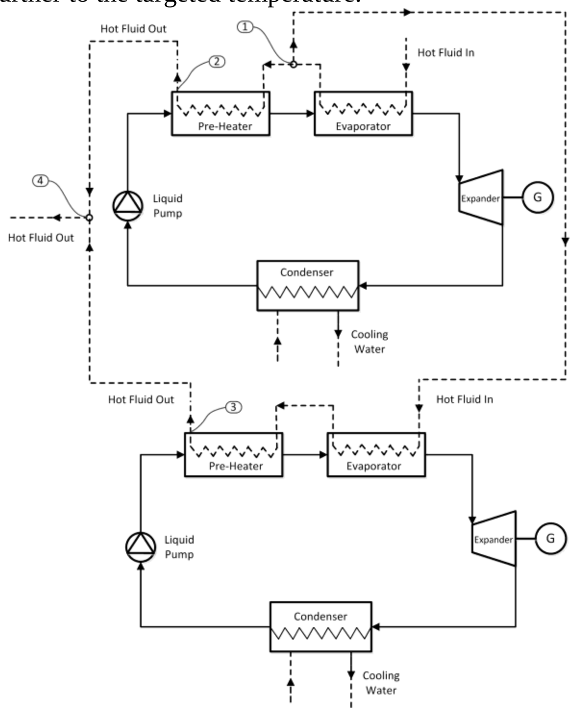

Fig. 3: novel cascaded organic Rankine cycles

If the thermal fluid requires a high temperature drop, the cascaded organic Rankine cycles can achieve much higher thermal efficiency than a single stage organic Rankine cycle. Table 2 shows a comparison between the single stage ORC and the cascaded ORC based on a real case of Sinopec Hainan Refinery. The hot medium water conditions are as follows:

- Flow capacity: 200 t/h.
- Water temperature: 118°C.
- Required returning water temperature: 70°C.

As shown in Table 2, at the same thermal fluid conditions and the same condensation temperature, the thermal efficiency of the cascaded ORC is 13.2% higher than the single stage ORC. The following conditions are applied to the analysis:

- The screw expanders used for the single stage ORC and the cascaded ORC have the same isentropic efficiencies. The refrigerant pumps, the generators and motors have also the same efficiencies.
- The evaporative condensers are used and the same condensation temperature are applied.
- The superheat from the evaporators is 0°C, which is only possible when the screw expanders are used.

For a single stage ORC, the evaporation temperature shall be defined according to the thermal fluid conditions and the heat balance. However, for cascaded ORC the evaporation temperatures of the high temperature loop and the low temperature loop can be optimized to achieve the highest thermal efficiency.

Table 2: cycle thermal efficiency comparison between the single stage ORC and the cascaded ORC

	Single stage ORC	Cascaded ORC
Hot water flow capacity（t/h）	200	200
Hot water temperature（°C）	118	118
Required water returning temperature（°C）	70.5	70.5
Condensation temperature（°C）	30	30
Model number of screw expanders	Kaishan SKYe297	Kaishan SKYe297
Isentropic efficiency of the expanders (%)	88	88
Refrigerant	R245fa	R245fa
Net power（kW）	800	907

Thermal efficiency based on the net power（%）	7.2	8.2

For the above hot gasoline ORC power plant, the required gasoline temperature drop is 55°C, which is very high, the cascaded organic Rankine cycles presented here can be used to achieve much high thermal efficiency. The reason why the author did not apply the cascaded organic Rankine cycles in this case is due to the following reasons: this is the 1st gasoline ORC power plant to be built as a part of the gasoline refineing process, and the 1st priority is the reliability instead of the thermal efficiency. The single stage ORC is used to reduce the complicity of the power plant.

4. AN ORC POWER PLANT WITH THE CASCADED ORC AND SCREW EXPANDERS USED FOR HOT MEDIUM WATER

According to the analysis and the optimization in the last section, the author applied the cascaded ORC shown in Fig. 3 in the power plant at Sinopec Hainan Refinery, Hainan Island, China. The annual average ambient temperature at Hainan Refinery is 25°C, which is the highest among all the refineries in China. July is the hottest month with the monthly average ambient temperature of 34°C. It is critical to apply the cascaded ORC to this application in order to achieve the highest efficiency year around. Fig. 4 shows the power plant installed at Sinopec Hainan Refinery. The power plant has been in operation since the end of May, 2014.

Fig. 4: the hot medium water ORC power plant installed at Sinopec Hainan Refinery, Hainan Island, China

The power plant has following specifications:

- Hot medium water flow capacity: 200 t/h
- Water temperature: 118.0 – 121.7°C
- Required water returning temperature: 70 – 73.4°C
- Generator nominal power of the high temperature loop: 710 kW
- Generator nominal power of the low temperature loop: 630 kW
- Generator voltage: 6300 V
- Generator type: induction
- Screw expanders for the low and high temperature loops: Kaishan SKYe297
- Explosion proof
- Design net power output at the annual average ambient temperature 25°C: 907 kW
- Design net power output at the hottest monthly average ambient temperature 34°C: 789 kW

Table 3 shows the qualification test results at the ambient temperature of 34°C (Zhejiang Kaishan, 2014). The real measured net power is 2.9% lower than the design value. The major reason for the lower net power output is that parasitic power is higher than the anticipated parasitic power. All the motors and generators used in the power plant are explosion proof. Although the high efficiency generators and motors are specified, the actual efficiencies did not reach the specified levels. The author also would like to point out that the screw expanders works very well in ORC cycles with the large ambient temperature variations. Although the pressure ratio or differential pressure across the screw expanders reduces significantly in the summer time compared with the design conditions, the screw expanders can still maintain very high isentropic efficiencies and thus the high net power output from the power plant.

Table 3: design and measured data of ORC Power Plant at Sinopec Hainan Refinery

	Design data	Measured data
Ambient temperature（°C）	34	34
Hot medium water flow capacity (t/h)	200	200
Medium water inlet temperature (°C)	121.7	120.0
Required water returning temperature（°C）	73.4	72.5
Medium water temperature drop (°C)	48.3	47.5
Net power output（kW）	789	767

5. DISCUSSIONS AND CONCLUSIONS

1. In oil refineries and chemical plants, there exist large amount of hot fluids, such as, the hot medium water for the refining processes, the condensed hot water, the hydrofining diesel and the hydrofining gasoline etc., which can be used to generate the power through organic Rankine cycles. At the same time, the cooling power and the cooling water can be saved. As the ORC power plants become a part of the refining or chemical processes, the power plants should be designed and installed according to the related standards and regulations with all necessary design redundancies, and the reliability of the ORC power plants are very important and critical.

2. If the hot fluid has a large flow capacity and requires a large temperature drop, the cascaded organic Rankine cycles presented in this paper can be used to achieve a much higher thermal efficiency. Based on a real application case at Sinopec Hainan Refinery, Hainan Island, China, the author compared the thermal efficiencies between the single stage ORC and the cascaded ORC. At the same hot fluid conditions, the thermal efficiency of the cascaded ORC is 13.2% higher than the single stage ORC.

3. Two ORC power plants installed in refineries are presented in the paper. The 1st ORC power plant is located at Sinopec Yanshan Refinery. It is with a single stage ORC, and powered by the hot hydrofining gasoline from the refining process. The 2nd ORC power plant is located at Sinopec Hainan Refinery. It is with the cascaded ORC, and powered by the hot medium water also from the refining process. Their design specifications and the qualification test results are also presented.

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